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The opposite of ubiquitous: How early adopters of fast-filling alt-fuel vehicles adapt to the sparsity of stations☆

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ABSTRACT

Transportation is proving to be the most difficult sector for reducing U.S. carbon emissions. With 86% of American commuters continuing to drive to work, meeting the urgent climate-change challenge requires a pronounced shift to alternative-fuel vehicles (AFVs). Standing in the way of this transition, however, is the dearth of conveniently located refueling and recharging stations. This paper argues that we cannot generalize from the refueling habits of people driving gasoline cars, or from their stated preferences for where they would need or want stations, because they formed those habits and preferences while using a ubiquitous network of gasoline stations. We also must distinguish among the different behaviors engendered by slow and/or home charging of electric vehicles, flexible refueling and recharging of hybrids and flex-fuel vehicles, and fast refueling/charging AFVs. Therefore, this paper reviews the limited literature on the revealed preferences of where actual early adopters of single-fuel, fast-filling AFVs choose to refuel or recharge when faced with the reality of a sparse network of stations. Refueling preferences have been revealed by (1) surveys asking drivers where they usually refuel, (2) intercept surveys at stations, and (3) GPS and card-swipe data. The few existing studies suggest that drivers adapt by focusing more on convenience of locations than price. Drivers refuel more frequently at the same stations, at higher tank or battery levels, more on work-anchored trips, more in the middle of trips, less often near home, more often on their way, and take larger detours compared with drivers of gasoline and diesel vehicles. To put these results in a broader context, the paper compares them briefly with revealed-preference results for slow charging of electric vehicles and with stated-preference results for hydrogen and similar fuels. The paper discusses the implications of these findings for the initial rollout of fast-refueling station infrastructure and identifies gaps in what we know about actual AFV refueling and recharging behavior.

1. Introduction and background

In February 2016, the transportation sector passed electric power generation to become the leading US source of greenhouse gas emissions. While all other sectors of energy use—electricity generation, industrial, residential, and commercial—have reduced their GHGs since 2013, transportation's emissions have risen 6.2% (US Department of Energy, 2016). There are many reasons why transportation remains stubbornly immune to GHG reductions (Sultana et al., 2017). One reason is the total automobile share of journey to work (drive-alone plus carpooling) has been relatively flat, declining only from 87.9% in 2000 to 85.7% in 2016 (Bureau of Transportation Statistics, 2017; US Census Bureau, 2018). The other part of the explanation lies in the forms of energy powering those cars. Other energy-use sectors enjoy a healthy competition among energy sources, whereas transportation is a virtual monoculture for energy use, relying on petroleum for over 92% of energy consumed, with biomass (5.2%), natural gas (2.3%), and electricity (0.09%) accounting for the remainder (US Department of Energy, 2017). Due to the fact that vehicles are mobile, switching to a less carbon-intensive fuel requires that alternative-fuel stations must be available over a wide area where that vehicle might travel. Due to its historical first-mover advantage and network externalities, petroleum-based gasoline and diesel are widely available. In addition, petroleum has greater energy density per unit weight and volume, which increases driving range and space for cargo and passengers. Factor in the public familiarity with gasoline and internal combustion engines, the availability of parts and repair shops, and the economies of scale in manufacturing, and the difficulty of transitioning away from petroleum fuels is not difficult to understand (Melendez, 2006).

After decades of research and development, manufacturers are

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commercializing alternative-fuel vehicles (AFVs), which are gaining traction with the public. Since 2000, the number of different types of alternative-fuel and advanced light-duty vehicle models sold in the US by original equipment manufacturers increased from 42 to 219 (Alternative Fuels Data Center, 2018a). The types of vehicles included in this tally include E85 (85% ethanol, 15% gasoline), compressed natural gas (CNG), diesel, electric vehicle (EV), hybrid electric vehicle (HEV), propane, hydrogen, and methanol. Excluding diesel and hybrid models that generate all of their original motive power from petroleum, the offerings still increased from 37 to 141. Globally, the number of electric vehicles passed 1 million in 2015 and 2 million in 2016. In Norway, EVs accounted for a 29% market share of new registrations in 2016 (International Energy Agency, E.V.I, 2017). In the United States, plug-in electric vehicle (PEV) sales, which include battery electric (BEV) and plug-in hybrid electric vehicles (PHEV), grew from 17,731 in 2011 to 113,869 in 2015, led by the Tesla Model S, Nissan Leaf, and Chevrolet Volt. NGV Global (2018) estimates over 26 million natural gas vehicles are operating worldwide. Toyota, Hyundai, and Honda are selling and leasing production-scale hydrogen fuel-cell vehicles (FCV) in California and several countries around the world.

Despite these successes, the AFV industry faces substantial barriers slowing the diffusion process, including range anxiety and a lack of available refueling stations in convenient locations (Franke and Krems, 2013; Melendez, 2006). The lack of stations discourages automakers from producing vehicles, which discourages fuel companies from building stations, in a chicken-and-egg dilemma (Shaheen et al., 2008). As of October 2018, there were 3282 publicly available E85 stations, 2486 EV fast-charging stations, 925 CNG stations, 196 biodiesel stations, 75 LNG stations, and 40 hydrogen stations (Alternative Fuels Data Center, 2018b. In percentage terms, the US is building up the number of stations rapidly, but for most fuels in most regions, the absolute number is a small fraction of the roughly 150,000 retail gasoline stations.[1]

There are a number of strategies for breaking the chicken-and-egg feedback loop. The “fleets-first” strategy incentivizes or mandates fleets of light- or heavy-duty vehicles to purchase and use some AFVs, which can include building a refueling station at their depot (Corts, 2010; Golob et al., 1997). The fleet station would provide central refueling to their out-and-back routes while providing built-in demand for fuel and publicly available pumps outside their fence for consumers and other fleets. This strategy has helped establish a starter network of E85 and CNG stations in particular, though Melendez (2006) has pointed out the difficulty of transitioning from fleets to consumers and Nesbitt and Sperling (1998) have examined several myths about the fleets-first strategy, such as that fleet vehicles rely solely on central refueling (Kelley and Kuby, 2017).

For AFVs targeted primarily at consumers, regions must construct a minimally sufficient network of stations in advance of commercialization. California, for instance, has started building a network of hydrogen stations, with 39 stations open to the public and 5,899 vehicles sold or leased as of January 1, 2019 (California Fuel Cell Partnership, 2019). The long-term competition between conventional and alt-fuel vehicles—incorporating the interplay of stations and vehicles, technological learning, economies of scale, supportive policies, and subsidies for fuels, vehicles, and stations—has been simulated extensively, indicating generally that some degree of government support is necessary in the early stages for the AFV industry to become competitive (Gnann and Plötz, 2015; Greene et al., 2014).

For these reasons, it is imperative that the initial network of alt-fuel stations be located wisely, based on a realistic understanding of how drivers use the infrastructure. This paper argues that the refueling behavior and stated preferences of gasoline drivers is not an adequate basis for planning stations because their current behaviors and preferences were developed given a nearly ubiquitous network of stations in most urban areas. In contrast, early adopters of AFVs must adapt to a much sparser network of stations and a shorter driving range. To make better evidence-based decisions, the bulk of this paper reviews in detail the small number of revealed preference studies that examined where real AFV drivers actually refueled or recharged their vehicles. The scope of the review, outlined in Section 2, focuses on fast-charging/filling vehicles and stations, such as compressed natural gas, which are comparable to gasoline, diesel, and hydrogen in refueling time (under 10 min), range (over 250 miles), and home refueling (rare). The main findings, broken down into nine different aspects of refueling behavior, are reported in Section 3 and compared to revealed behavior of gasoline drivers. Section 4 then briefly compares the findings to those for slow charging of EVs and stated preference for hydrogen fueling. Finally, Section 5 discusses location strategies given what we know about AFV fast-filling behavior. This section aims more at the general research community and decision-makers, but also explores implications for optimization modeling. The paper concludes by identifying knowledge gaps and highlighting opportunities for transportation geographers in this and other AFV-related research areas.

2. Scope of review

2.1. Scope of review

The main goal of this paper is to review the very limited literature on revealed preference of fast-filling AFV refueling behavior—that is, where do AFV drivers refuel or fast-charge their AFVs. Several key distinctions in this scope require justification.

First, this review focuses on revealed-preference surveys. It is well known that what survey respondents say can differ substantially from what they actually do. In the particular case of refueling, there are specific reasons to question what drivers of conventional vehicles say. Gasoline drivers are accustomed to station availability that is, for practical purposes, nearly ubiquitous (Fig. 1 top). Most drivers have multiple stations to choose from that are both near and on the way to home, school, work, or shopping, and often choose based on price and amenities (Funderburk, 2017). What drivers who are accustomed to having so many convenient choices say they want/need/would do may not accurately reflect what they actually do when faced with the sparse availability of AFV stations (Fig. 1 bottom). However, after Section 3's main review of revealed preference survey results, Section 4 briefly compares the findings to those from stated preference surveys for alt-fuel station locations by gasoline drivers.

Second, this paper focuses on fast-filling and fast-charging behavior. Level 1 charging (110 V AC standard US outlets) provides 4–5 miles of driving range per hour of charging (mRph), while Level 2 (240 V AC) adds 20–25 mRph. Slow charging makes sense for recharging while doing another activity, such as working, shopping, eating out, appointments, entertainment, or being at home, and for emergency charging to avoid getting stranded. These slower charging stations have been around the longest, and are deployed mainly through a sales-driven business model rather than spatial analysis, and are relatively inexpensive to install. In contrast, stations for fast EV charging, EV battery swapping, and liquid and gas refueling of B20, E85, CNG, LNG, and H2 cost from several hundred thousand to millions of dollars to build, and refueling time is similar to that for gasoline (Ito et al., 2013; Mazloomi and Gomes, 2012). Section 4 briefly compares the fast-filling/charging findings to revealed preference studies on slow charging.

Third, this review focuses on refueling behavior and station choice, not refueling “demand.” Demand for fuel or charging is a function of

[1] According to http://www.convenience.org/YourBusiness/FuelsCenter/Pages/Who-Sells-Americas-Fuel.aspx#.WqhsVWrwZGo, 122,552 convenience stores currently sell fuel in the United States (Feb.,2018). As of 2013, the last issue of National Petroleum News Market Facts counted almost 153,000 total retail sites also including grocery stores, service stations, and hypermarkets.

Fig. 1. Gasoline stations in zoomed-in area of Boston and central suburbs, located by author (top). CNG stations in the greater Boston area open to the public and other fleets, from NREL Station Locator (bottom). Both maps from January 9, 2019.

where drivers refuel but also of AFV ownership and driving patterns. There is a substantial literature profiling AFV purchasing, which has been reviewed elsewhere (Coffman et al., 2016), but far less on where owners actually refuel.

2.2. Revealed preference studies and methods

Only a handful of revealed-preference studies of actual fast-filling AFV drivers have been published to date. Even including a few studies of gasoline filling for comparison purposes yields a small number of studies. The author relied on keyword searches and forward and backward citations from known studies using Google Scholar. No limitations were placed on the universe of academic journals.

Researchers have used three types of methods to explore station choice by drivers. First, some surveys simply ask drivers which station (s) they frequent, as well as information about their home, work, and other locations. Plummer et al. (1998) interviewed gasoline drivers in St. Cloud, Minnesota, USA about their "choice sets" of stations from which they generally choose. Bunzeck et al. (2010) combined revealed and stated preference questions by asking 2970 Dutch drivers about their actual gasoline refueling habits as well as their stated refueling preferences for purchasing a hydrogen FCV. Brey et al. (2016) conducted a phone survey of 230 gasoline drivers in Seville, Spain about where they refuel, and why. All three studies surveyed drivers using gasoline.

Second, researchers have conducted intercept surveys of drivers while they refueled, following the pioneering work of Kitamura and Sperling (1987) and Sperling and Kitamura (1986) at gasoline stations in California. Diesel drivers served as proxies for future AFV drivers. Diesel cars, however, tend to have among the longest driving ranges and diesel stations offer far better coverage than early alt-fuel networks. Decades later, Kelley and Kuby (2013) conducted intercept surveys for CNG drivers in Southern California. With thousands of OEM Honda Civic NGVs as well as pickup trucks, vans, and converted sedans owned by private citizens, and about 80 publicly available CNG stations, SoCal was one of the only US regions where this type of natural experiment could be conducted on actual AFV drivers at that time. The Honda Civics had a driving range of 250–300 miles per fill-up. Kuby et al. (2013) compared the CNG drivers' refueling patterns to those of a control group of customers at a nearby gasoline station, while Kelley and Kuby (2017) analyzed responses from commercial fleet drivers of CNG vehicles intercepted at the same stations. Kelley (2017) intercepted drivers at CNG stations in close vicinity to Southern California freeway interchanges to try to assess perceptions and patterns surrounding the unique locations. These four studies of actual AFV drivers by Kuby and Kelley, however, share similar limitations: they were conducted at stations located at commercial or municipal fleet bases in commercial and industrial areas in freeway-centric Southern California where SOV-drivers of CNG vehicles get HOV-lane privileges. Finally, in a less-developed country setting, Pramono and Oppewal (2013) intercepted 287 consumers at seven gasoline stations in Bandung, Indonesia.

Third, studies are now emerging that use GPS and/or card-swipe data to reveal refueling decisions. Sun et al. (2015, 2016) used card-swipe data matched with vehicle GPS route data for fast charging at workplaces, car dealers, parking lots, convenience stores, gas stations, and leisure sites in Japan for EVs with driving ranges of 120–180 km. Their study focuses on mid-trip refueling, rather than at the origin or destination. Nicholas et al. (2017) used data from over 1 million fast-charging events at EVgo chargers in California in 2014–16, mostly for Nissan Leafs. Morrissey et al. (2016) studied 10,714 fast-charging events at 83 fast-chargers at petrol stations on motorways and at car parks in Ireland and Northern Ireland from 2012 to 2015.

3. Review of revealed preference findings for fast-filling AFVS

Using revealed-preference refueling data, the studies above analyzed a number of different spatial aspects of refueling station choice including trip anchors, tank/battery level, habituality, detouring, distance, and type of location. We compare as many studies as possible on each criteria, recognizing that different studies analyzed some but not all of these factors. Given the limited number of studies and the difficulty of comparing their findings, all generalizations are speculative and bear testing in different regions with different kinds of AFVs.

3.1. Criteria for choosing a station

Before reviewing the academic papers more specifically geared toward AFVs, it is useful to summarize gasoline industry reports about how drivers choose stations. Founded in 1961, NACS - The Association for Convenience and Fuel Retailing (2017) conducts an annual online survey of over 1000 drivers. Their emphasis on price diminished during the 2010s but was still ranked most important by 61% of drivers in 2017, while location grew more important, rising to 25%. To save 5¢ per gallon, 64% said they would make a left turn across a busy street, while 67% said they would drive 5 min out of their way, which drops to 38% for a 10-min detour. In a market research survey of over 11,000 American consumers, price led all factors with 77% of respondents rating it highest importance on a Likert scale, followed by lighting (49%), fuel quality (48%), and payment option (47%) (Funderburk, 2017). The first location-related factor—ease of getting in and out of the location— appears in 5th place at 43%, but deals more with site than situation. This is followed by "location is nearby when my "empty" warning light goes on in my car" at 36%. After that comes a long list of factors dealing with loyalty programs, appearance, brand reputation, service, food and coffee, air pumps, car washes, and phone apps.

Turning to the academic research, Table 1 summarizes drivers'

Table 1
Criteria for choosing a station ranked as most important.

Criteria (First Choice)	Sperling and Kitamura, 1986 –Gasoline –N. Calif. (n = 1472)	Plummer et al., 1998 –Gasoline -St. Cloud, MN (n = 301)	Bunzeck et al., 2010* -Gasoline –Holland (n = 2970)	Kuby et al., 2013 –Gasoline -S. Calif. (n = 267)	Sperling and Kitamura, 1986 –Diesel –N. Calif. (n = 107)	Kuby et al., 2013 –CNG –S. Calif. (n = 259)
Fuel Price	34%	32%	66%	6%	24%	6%
Convenient Location	29%	32%	35%	27%	56%	40%
- to Home	*21%*	n.a.	n.a.	n.a.	n.a.	n.a.
- to Work/ School	*8%*	n.a.	n.a.	n.a.	n.a.	n.a.
- Habitual Route	n.a.	n.a.	*35%*	n.a.	n.a.	n.a.
Near Freeway	5%	n.a.	n.a.	n.a.	n.a.	n.a.
Running out of fuel	13%	n.a.	n.a.	9%	6%	6%
Other	24%	37%	30%	n.a.	14%	n.a.

n.a. = not applicable (category not reported).
* More than one answer allowed and criteria not ranked.

stated reasons for choosing a station. Differences in methodologies and questions asked, however, make direct comparisons difficult. For instance, all six studies asked drivers whether convenient location was the key criteria, but defined "convenience" differently. Nevertheless, several tentative generalizations emerge from these studies. First, gasoline drivers pay more attention to price, while AFV drivers pay more attention to convenient location. This is especially clear in the paired samples of gasoline and diesel drivers by Sperling and Kitamura (1986) and the paired samples of gasoline and CNG drivers by Kuby et al. (2013).

Another generalization that makes intuitive sense is that far fewer AFV drivers chose a station because they were running out of fuel. Previous studies distinguished between planned or regular refueling and ad hoc, impulsive, or "on the fly" refueling (Kitamura and Sperling, 1987; Pramono and Oppewal, 2013). AFV drivers appear to plan their refueling stops more carefully because of range anxiety.

3.2. Trip Anchors

Intercept surveys at stations afford researchers the opportunity to ask drivers about their previous and next stops (Kitamura and Sperling, 1987; Kuby et al., 2013). Plummer et al. (1998) also reported on the driver's trip purpose, as reflected by their next destination. Table 2 attempts to compare the results of the four surveyed populations by collapsing the results into the percent of trips anchored at different kinds of locations. For instance, home-anchored trips are the sum of all refueling trips originating at home plus the sum of all trips ending at home, minus the trips from home to station and back to home, which would otherwise be counted twice. For Plummer's study, which produced a vector of trip purposes rather than a matrix of previous and next stops, we attempt to account for that by including the respondents' first and second ranked trip purposes.

Kitamura and Sperling's (1987) results from Northern California have been cited frequently in the debate about whether station location models should aim to locate fuel stations near customers' homes. They found that 75% of gasoline refueling trips either start or end at home. Decades later, Kuby et al. (2013) found an even higher percentage (86%) of home-anchored trips by gasoline drivers in Southern California. The percentage was 10% lower among CNG drivers but still above 75%. Thus, there can be little doubt that drivers of all kinds of vehicles frequently refuel going to or from home. The main difference revealed by the CNG study is a much higher percentage of work-anchored trips for CNG drivers, even compared with gasoline drivers at nearby control stations. It is unknown how much this is due to (a) the location of stations at fleet bases, (b) the fact that the primary reason the CNG drivers in the survey bought their vehicle was for HOV lane privileges (32% ranked it first), or (c) simply an adaptation to the sparser network of stations. What it does show, in any case, is a willingness of early adopters to rely heavily on work-anchored refueling. In fact, single-purpose round trips from work to stations and back were not uncommon (11%).

Table 3
Tank and battery levels when stopping to refuel.

	Kuby et al., 2013 –Intercept –Gasoline -S. Calif. (n = 267)	Kuby et al., 2013 –Intercept –CNG -S. Calif. (n = 259)	Sun et al., 2016* -GPS -Fast Charging –Japan (n = 3900)
Over Half	2%	8%	~50%
3/8	3%	8%	~26%
¼	31%	31%	~23%
1/8	25%	26%	~1%
Empty	39%	27%	0%

* Estimated by visual inspection of bar chart for private vehicles on workdays. Sample size is number of charging events reported for private vehicles.

3.3. Tank/battery level

We already reported that fewer AFV drivers chose their station because they were running out of fuel. Table 3 includes Sun et al.'s (2016) study of EV fast-charging in Japan, in which the state of charge (SOC) of the battery when it was first plugged in was recorded exactly. Their study reports SOC frequency distributions for all four combinations of private/commercial drivers and working/non-working days. Perhaps because of the shorter driving range of the Nissan Leafs at that time, drivers rarely allowed their batteries to drop below 10% SOC, and a much higher percentage charged with the battery over 50%. The commercial EV drivers more frequently charged at higher SOCs, perhaps because they drive more miles daily than private drivers.

CNG drivers, with longer driving ranges, refueled less frequently than EV drivers above the ¼ level, but more often than gasoline drivers (Kuby et al., 2013). Surprisingly, 27% of CNG drivers reported refueling with their tank on empty. Not included in Table 3 are results from Sperling and Kitamura (1986), who reported only whether drivers listed "running out of fuel" as a reason for selecting a station. The fact that 13% of their 1527 gasoline drivers listed "running out of fuel" compared with only 6% of their 107 diesel drivers confirms the greater cautiousness of AFV drivers.

Sun et al. (2015) used a stochastic frontier model to investigate more deeply whether EV drivers recharged earlier than necessary. Using the eventual EV trip ends and locations of other stations "downstream" of where the drivers recharged, they found that fast-charging commenced 14–19 km earlier than necessary, which they attributed to range anxiety among EV drivers. Surprisingly, higher capacity batteries and experience with the EVs did not improve this inefficiency.

Table 2
Percentage of refueling trips anchored (start and/or finish) at a location type.

Trip Anchor (ΣOrigin + ΣDestination – Both)	Kitamura and Sperling, 1987 –Intercept –Gasoline −N. Calif. (n = 1521)	Plummer et al., 1998 -Stated Preference (1st or 2nd Ranked) –Gasoline -St. Cloud, MN (n = 301)	Kuby et al., 2013 –Intercept –Gasoline −S. Calif. (n = 267)	Kuby et al., 2013 –Intercept –CNG −S. Calif. (n = 259)
Home	75%	n.a.	86%	76%
Work	29%	32%	56%	68%
School	n.a.	4%	5%	6%
Shop	39%	29%	13%	11%
Personal Business	10%	7%	n.a.	n.a.
Social	29%	20%	27%	22%
Single-Purpose Refueling from Home	7%	8%*	1%	1%
Single-Purpose Refueling from Work	3%		5%	11%

n.a. = not applicable (category not reported).
* Defined as "special trips," with no origin specified.

Table 4
Habituality of refueling at the station where the survey was conducted.

	Sperling and Kitamura, 1986 –Gasoline –N. Calif. (n = 1526)		Kuby et al., 2013 –Gasoline –S. Calif. (n = 267)		Sperling and Kitamura, 1986 –Diesel –N. Calif. (n = 107)		Kuby et al., 2013 –CNG –S. Calif. (n = 259)	
Over 50%	45%		21%		66%		37%	
25–50%	17%		52%, of which −13% exactly 25%	50% − 26% from 26% to 49%	20%		52%, of which −5% exactly 25%	28% exactly 50% − 19% from 26% to 49%
Less than 25%	38%		27%		14%		11%	

3.4. Habituality

With fewer stations available, one would expect AFV drivers to plan their refueling stops more deliberately and patronize the same stations more frequently. Two surveys asked drivers about their "habituality" of refueling (Table 4). Sperling and Kitamura (1986) reported three categories of habituality, which show a 21 point increase from gasoline to diesel drivers in the percent refueling at the same station over half the time, and a 24 point drop in the percent doing so less than one-quarter of the time. Kuby et al. (2013) included an open-ended question: "How frequently do you refuel at this particular station?" If we label refueling at the same station over 50% of the time as highly habitual, and under 25% as ad hoc, then CNG drivers reported 16% more highly habitual refueling than gasoline drivers, and 16% less ad hoc refueling.

3.5. Beginning, middle, or end of trip

Whether one refuels in the beginning, middle, or end of a trip may sometimes be dictated by the trip length, starting tank level, and availability of refueling *en route*. If unconstrained, few drivers on urban trips would be expected to interrupt their trips to refuel mid-way, especially if it involves exiting and re-entering a freeway. Another reason why refueling locations would be clustered at the beginning or end of a trip is that drivers prefer areas familiar to them (Kitamura and Sperling, 1987). AFV drivers, however, may not have a station anywhere near their origin or destination, and may have no other choice than to refuel mid-trip. The willingness of AFV drivers to refuel mid-trip is critical to whether stations can be sited near highway exits on busier, more centrally located freeways.

Three studies report results on mid-trip refueling for gasoline and AFV drivers. Kuby et al. (2013) proposed a metric that computes the distance from origin to station as a percentage of the total route distance from origin to station to destination. Fig. 2 compares their findings to similar data obtained from Sun et al.'s (2016) analysis of fast charging in Japan, and data estimated for Kitamura and Sperling's (1987) analysis of gasoline refueling from their matrix of travel times from origin and destination.[2]

Neither of the two distributions for gasoline refueling fit the U-shaped hypothesis: Kitamura and Sperling's (1987) results for Northern California were heavily weighted to refueling near the beginning of trips, while Kuby et al.'s (2013) results for Southern California create a fairly flat distribution. In contrast, the two alt-fuel studies both display a *reverse* U shape that peaks in the middle of trips, despite the many differences between EV fast charging and CNG refueling. The reverse U in Sun et al.'s distribution is less pronounced as well as skewed toward the destination, perhaps because of the availability of home recharging.

3.6. Detouring

Only two studies used the locations of the trip's origin, destination, and refueling station to compute a revealed willingness to detour for AFV refueling. The calculation is straightforward: the difference in the distance or travel time between optimal routes with and without the station stop is equal to the deviation. Sun et al. (2016) found that about 10% of private EV drivers in Japan did not have to detour at all to fast-charge their EV, and over 50% deviated less than 1 km. Detouring behavior is consistent with their statement that the choice for a fast-charging station for a BEV "takes place while driving a route from origin to destination" (p. 34). At five CNG stations in Southern California, Kuby et al. (2013) found a plateau out to about 6 min of deviation before one starts to see a drop-off in the number of drivers

[2] The mid-point of each time category was used, e.g., 2.5 min for the 0–5 min category. For the over-30-min category, 35 min was used. Stations located 0–5 min from both origin and destination were omitted from the analysis.

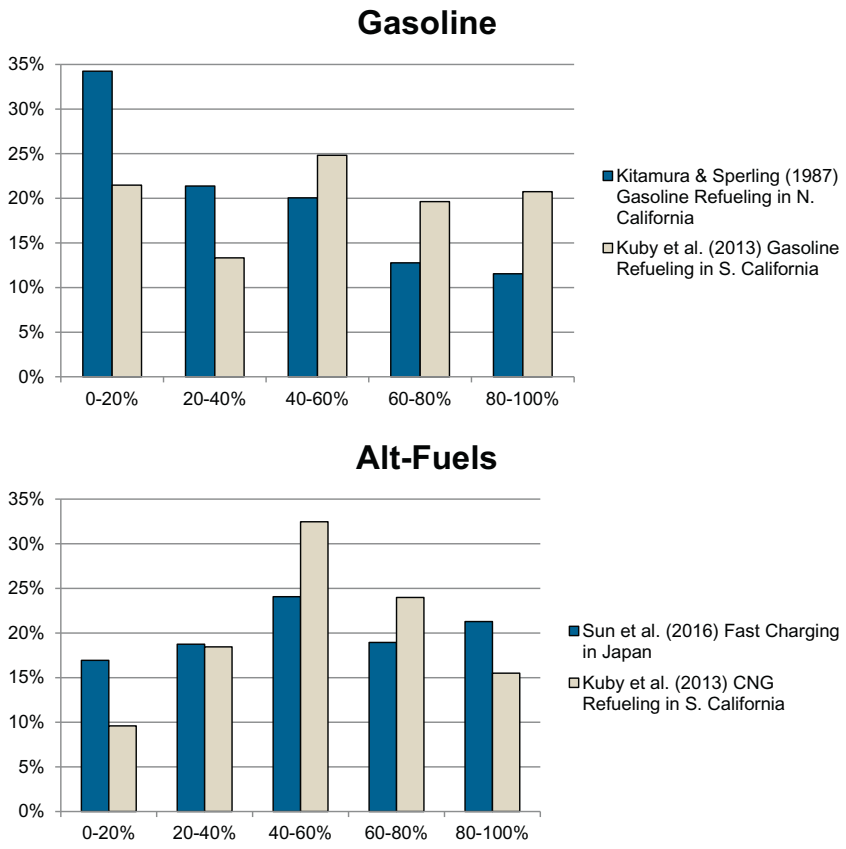

Fig. 2. Refueling location by percentage of distance or travel time along route, from 0% (origin) to 100% (destination).

deviating. In contrast, at nearby gasoline stations, the decay curve shows no plateau, just a classic decay curve with most drivers deviating 0–3 min. The latter finding is consistent with (Pramono and Oppewal, 2013), who estimated a detour of 1.5 km as the highest likelihood for gasoline drivers in Indonesia.

Kuby et al. (2013) also asked drivers whether they subjectively felt that accessing the station required a detour. The comparison with their actual deviations helps distinguish between what an early AFV adopter is willing to do vs. would like to do. An equal number of CNG drivers detoured 0–3 min and 3–6 min, but only 29% of the former group stated that it felt like a detour to them, while 51% of the latter group considered it a detour. What is unknown is whether this perception of detouring and willingness to detour is characteristic only of the enthusiastic early AFV adopters or would it extend to the early and late majorities.

3.7. Distance from home

There is a widespread assumption and ample evidence that "consumers typically prefer to buy gasoline at stations in the vicinity of their residence" (Pennerstorfer, 2009). Kitamura and Sperling (1987) found that 43% of gasoline drivers refueled within 5 min of home, and 60% of those who did so reported using that station more than half the time. The relevant question is not whether people rely heavily on stations near their homes when such stations exist, but what do they do when stations are rare and only some people have stations near their homes?

In Kuby et al.'s (2013) study in Southern California, CNG drivers refueled a median network distance of 8.3 miles from home. The results at least show a willingness to refuel farther away from home than gasoline drivers did at similarly located gasoline stations, which had a median distance of 3.3 miles from home.

For fast charging of EVs, Nicholas et al. (2017) found median network travel distances of 13.6 miles for paid charging, and 6.8 miles for free charging. These short revealed-preference distances suggested that free fast charging was being used as a substitute for paid home charging or by drivers who lack home charging, or that drivers are using other household vehicles for longer trips.

3.8. Near home or on the way?

For near-home refueling, many studies reference the 75% of drivers who refueled on home-anchored trips in Kitamura and Sperling (1987). Yet, this same paper points to "locations along high-volume commuting routes" as strategic locations of initial fuel outlets. Very few studies have compared consumer preferences for these two strategies.

Kelley and Kuby (2013) designed a revealed-preference study to disentangle the near-home and on-the-way definitions of convenience. Extending the deviation analysis from Kuby et al. (2013) described above, they estimated the detour in miles and minutes as well as the travel time and distance from home for every possible CNG station at

Table 5
Classification of actual choice of cng stations by 259 drivers in greater Los angeles (Kelley and Kuby, 2013).

Convenience Criteria	Refueled at Closest Station to Home	Refueled at Station Not Closest to Home
Refueled at Station with Smallest Deviation from Shortest Path	"Both" 59	"Least Deviation" 102
Refueled at Station Not with Smallest Deviation	"Closest to Home" 10	"Neither" 88

which a driver could have refueled. Knowing where these drivers actually refueled, they determined if the driver refueled at the station closest to home, most on the way, both, or neither (Table 5). Drivers who filled at a station that optimized both convenience criteria did not face a difficult decision, while drivers who filled at a station optimizing neither criterion did not reveal a clear preference. Focusing on the drivers who optimized one or the other, however, more than 10 times as many drivers chose the station on their way over the station closest to home. Digging deeper into the numbers, they found that for 8 of the 10 drivers choosing the station closest to home, that station was also top 3 in shortest deviation. Looking at the 102 drivers choosing the station with the shortest deviation, only 51 chose a station that was among the three stations closest to home. While these strong results may not be transferable to other fuels besides CNG and other regions outside of Southern California, they provide strong evidence that drivers at least learn over time that on-the-way refueling saves time, even if the station is far from home.

For EV fast charging in Japan, Sun et al. (2016) did not report data on the home locations of drivers, preventing direct comparison to Kelley and Kuby's findings. In addition, EV home charging likely reduces the need to charge near home. However, they did find that 18% of EV drivers fast-charged at a station where either the origin-station distance or the station-destination distance exceeds the origin-destination distance. One out of six drivers thus recharged somewhere that clearly took them away from or past their destination. We do not know whether the origin or destination is “home” or what the next-best choice would have been for these drivers, but there is evidence here of some drivers going in the wrong direction to fast-charge near an origin or destination.

3.9. Location type

If drivers of fast-filling alt-fuel vehicles are willing to refuel mid-trip and detour slightly off their shortest paths, and frequent stations with short deviations even if others are closer to their home, then placing them near busy intersections of two or more freeways may make sense because of the large traffic volumes passing through. Kelley (2017) intercepted around 40 drivers at each of four CNG stations near freeway intersections in Greater Los Angeles. Three of the stations were located less than one mile from the center of a four-way or five-way freeway intersection. Kelley classified the refueling trips as involving surface streets only (15%), singly freeway-anchored (37%), or doubly freeway-anchored (48%). Doubly anchored implies the driver's fastest O-D path involved getting off a freeway, visiting the station, and getting back on a freeway. More than half of the respondents stated that the station was not convenient to their home location but also that it was conveniently on their way. An overwhelming majority agreed that the station was not visible from the freeway. Drivers refueled on trips averaging 26 miles long and deviated an average of 7 min from their shortest path. Asked which other stations they considered (i.e., their choice set), over 45% said they considered one of the other nine stations near freeway intersections besides the one at which they refueled.

Two studies distinguished among different kinds of host sites for EV chargers. Morrissey et al. (2016) found that fast chargers at car parks in Ireland and Northern Ireland averaged 1.15 charge events per day, compared with 0.48 at petrol stations on motorways. In Japan, however, Sun et al. (2016) found that drivers preferred fast chargers at gas stations over those at workplaces, leisure places, car sales outlets, parking lots, and convenience stores. More research is needed in different study areas to test whether any such general preference exists.

4. Brief review of related literatures

The previous section reviewed revealed-preference studies that demonstrate how drivers adapt to the scarcity of alt-fuel stations. It focused mostly on CNG and diesel vehicles, which are directly comparable to gasoline vehicles because they fill quickly and are not (or are rarely, in the case of CNG) filled at home. Selected revealed preference results for EV fast-charging behavior were also reported while acknowledging that findings for EV fast-charging and liquid and gaseous AFV refueling may have limited applicability to the other. This section briefly considers two additional sets of studies that differ in even more significant ways from the core studies in Section 3 but are included to provide a wider perspective on refueling behavior. Section 4.1 provides a short overview of revealed-preference studies of EV slow-charging behavior, while Section 4.2 summarizes results from some stated-preference surveys.

4.1. Revealed preference for slow charging of EVs

Usage data for EV slow chargers (Level 1 and 2) has been collected and studied for at least a decade, and can be considered a form of aggregate revealed preference analysis. Because many early EV drivers had home charging available, most studies have found that public slow charging infrastructure is lightly used but occurs more where people park their EV and perform another activity for a period of time. Van den Hoed et al. (2013)—one of the largest early studies of actual charger usage based on 260 charging locations and 135,000 charge sessions—found an average of 1.62 charge sessions per day in 2012–13. This study found a large difference between average capacity utilization time of 7.25 h (when a charger is connected to an EV) and a charging time just over 1 h (when the EV receives electricity). Morrissey et al. (2016) monitored 711 charge points across Ireland, of which 83 were fast chargers. Classified into use cases, they found highest utilization for fast chargers at parking lots (1.15 charges/day) and petrol stations (0.48). Slow chargers were used 3–5 times longer per session, but in fewer daily sessions at parking lots (0.14 per day), on-street (0.13), multi-modal transit stations (0.07), and petrol stations (0.06). Smart's (2012) analysis of data from the US's EV Project found the most charging events at workplaces followed by parking lots, public municipal locations, transportation hubs, and retail, with median number of daily charging sessions between 1 and 1.34. Smart and Schey (2012) found that only 18% of charging took place away from home—at shopping centers, health clubs, bars and restaurants, office buildings, and other homes. Franke and Krems (2013) found 83.7% of charging sessions took place at home and 11.5% at normal sockets, with only 4.8% at public charging stations. In the UK's CABLED project, Aston University (2012) found home charging sessions outnumbered workplace charging by more than 3X, and public locations by > 4X. These studies have rightly focused on parking patterns, because that is when the vast majority of slow charging takes place.

Plug-in hybrid electric vehicle (PHEV) charging is different than for pure battery electric vehicles (BEVs). Morrow et al. (2008) found that PHEV drivers charged them on only 19% of trips and were mostly plugged in at home in the evening. Tal et al. (2014) found that small-battery PHEV drivers charge at public stations less frequently than large-battery PHEV drivers, possibly because there is less incentive to charge a smaller battery when the car can run on gasoline when the battery is depleted.

4.2. Stated preference for refueling availability

Numerous stated preference studies have posed hypothetical choices to drivers about purchasing an FCV or other AFV, which are analyzed using discrete choice models. For a review, see Liao et al. (2017). Since refueling availability is just one factor of many that are typically included, these revealed preference studies tend to represent refueling availability in terms of a simple criterion involving a single station, such as distance from home or in one's community (Krause et al., 2013; Rasouli and Timmermans, 2016) or deviation from regular driving route (Caulfield et al., 2010; Hoen and Koetse, 2014; Lines et al., 2008; van Amelsfoort and Zwier, 2007), or more commonly as a

percentage of existing gas stations with alt-fuel available (Greene, 1996; Hackbarth and Madlener, 2013; Potoglou and Kanaroglou, 2007; Sperling and Kurani, 1987; Ziegler, 2012). The vast majority of these stated preference studies confirm that whatever infrastructure availability question was posed was indeed important to buyers. A few, however, stand out for comparing more detailed and varied geographic alternatives.

Brey et al. (2016) asked drivers in four cities in Andalusia, Spain about three main factors for choosing a gasoline station: proximity (to home or a destination), location on the way, and other refueling station characteristics. Respondents could choose more than one answer. Proximity was listed alone or in combination with refueling station characteristics by 56.5%, compared with 28.3% for location on the way. Bunzeck et al. (2010) asked drivers about their willingness to switch to a more sustainable fuel based on infrastructure availability. Fully half stated that stations would need to be sufficient to cross the Netherlands or to travel abroad. The remaining responses include "in the neighborhood with less than a 5- or 10-minute detour" (combined 17.7%), 1–3 stations "along my daily route" (combined 11.6%), and "at my usual filling station" (20.4%) but with no indication of which category(ies) their usual station fits. Ito et al. (2013) asked respondents about different types of stations at different types of locations, and found a higher willingness to pay for fast battery exchange stations and hydrogen stations than normal or fast recharging at supermarkets. Finally, Melaina et al. (2013) showed survey participants hypothetical maps of hydrogen stations and found that willingness to purchase fell dramatically with density below 10% of the existing gasoline station density.

The more geographically detailed stated preference surveys indicated a lesser importance for stations along the way than in the one revealed preference study by Kelley and Kuby (2013) of CNG drivers in Los Angeles. This could mean that drivers adapt once they start facing the sparsity of AFV stations, or it could suggest that the infrastructure criteria for maximizing AFV adoption might align more with the gasoline refueling experience of potential adopters.

5. Discussion

5.1. Limitations

Though more reliable in principle than stated-preference studies, these revealed-preference studies have numerous limitations. The various Kuby and Kelley intercept surveys were conducted with CNG drivers in Southern California at stations originally built to serve fleets. These locations may not be representative of where most gasoline drivers refuel. Also, greater Los Angeles is a highly congested, freeway-centric region, and the leading reason given by CNG drivers for owning a CNG vehicle was for freeway HOV-lane access (32%) (Kuby et al., 2013). While HOV access is a widely offered and highly effective incentive for AFVs, it does bias the sample toward freeway drivers.

There are so few revealed preference studies of actual AFV drivers that it was necessary to include as many as possible, even if they are not strictly comparable to each other. Sperling and Kitamura (1986) studied diesel drivers as a proxy for AFV drivers, but the stations are far more ubiquitous, so one would expect the behavior to more closely resemble that of gasoline drivers. The fast-charging of EVs studied by Sun et al. (2016) is still slower than CNG, diesel, or hydrogen refueling. Also EV fast-charging cannot be viewed in isolation from home charging and slow charging while parked. It is likely that drivers plan their fast-charging sessions in coordination with these other options, which are largely not available to AFVs that run on liquid or gaseous fuels (CNG home refuelers do exist, but few drivers have them).

Readers are asked to consider these limitations in interpreting the results, and are encouraged to conduct similar studies in different regions with different incentives, station locations and densities, vehicle types, and driver populations.

5.2. Planning implications

The main implication of these limited findings is that actual drivers of fast-filling and fast-charging AFVs behave differently than drivers of gasoline and diesel vehicles. Gasoline and diesel drivers have countless stations from which to choose, and can afford to shop for low fuel prices and wait until their tank is nearly empty. Most gasoline drivers in urban areas can easily find a station that is both near home and on their way regardless of where they are going. They can therefore satisfy both criteria of convenience and still consider other factors such as fuel price, no left turns, and desired station amenities while avoiding stations that require them to deviate substantially from their shortest paths, exit and reenter a freeway, or navigate in the vicinity of freeway interchanges. In other words, drivers of conventional vehicles have the luxury of being picky about where they refuel, or of not planning their refueling whatsoever.

When stated-preference surveys ask about the station infrastructure necessary to convince them to buy an AFV, their answers tend to reflect this experience. Even the questions asked by researchers often reflect their own gasoline refueling experience, with many stated preference studies framing the question in terms of how close a station would have to be to one's home, or percent of gasoline stations offering alt-fuels. It is tempting, therefore, to conclude that stations should be sited close to early adopter neighborhoods.

When we look at the actual behavior of first adopters, however, we see different behavior. Faced with a shorter driving range *and* a scarcity of stations, early adopters refuel more deliberately and rely on a smaller choice set of stations. AFV drivers eschew stations close to home if they are not on their way, and are more willing to refuel on work-anchored trips, to exit and re-enter freeways, and stop for fuel in the middle of trips. They are willing to make longer deviations to refuel—but not too much longer. Early adopter consumers thus adapt to the sparse station network in common sense ways.

These findings have several implications for planning the initial networks of stations. The main implication is to emphasize locations that are along major high-volume highways, and preferably near the intersection of multiple high-volume roads or freeways. These locations can capture very high volumes of passing traffic capable of accessing such stations with short deviations. Locating stations in targeted neighborhoods for near-home refueling can provide convenient access to only a small population.

It is possible, however, to plan stations to achieve both kinds of convenience. Stations can be planned *for* targeted neighborhoods without being centrally located *in the middle* of them. Instead, if they are placed where such drivers funnel onto freeways, the stations would still be convenient to home while actually being on the way for *more* drivers from that neighborhood. Importantly, this would also make it possible for tens or hundreds of thousands of drivers from other areas to stop there while passing through. This strategy is consistent with Nicholas's (2010) analysis of gasoline sales, which correlated better with trades areas based on this funneling-to-freeway-exits concept than with trade areas based on traffic volume or population alone. It also alleviates some equity concerns of targeting stations solely toward neighborhoods that fit the profile of wealthier, better-educated buyers in multi-car households as the typical early AFV adopters. At the same time, freeway-based stations in such neighborhoods may alleviate the anecdotal concerns noted by Kelley (2017) that perceptions of neighborhood safety are important in drivers' choice sets of stations they consider.

To supplement these stations, high-volume freeway exits and interchanges in primarily commercial environments, such as CBDs, suburban downtowns, airports, universities, mega-malls, and other trip attractors should be strongly considered. The revealed preference studies show AFV drivers engage in almost as much work-anchored refueling as home-anchored. A dearth of local residential population should not eliminate busy and safe locations from consideration.

These behavioral findings and associated strategies have major

implications for optimal location modeling. Numerous studies (Hong and Kuby, 2016) have classified the modeling literature based on the nature of the spatial demands that the stations are serving: nodes (points representing zonal populations), arc traffic volumes, origin-destination trip volumes (flows, paths), and more sophisticated trip chains, tours, and time-space activity patterns. The revealed preference literature reviewed here is more consistent with the use of arcs, paths, and tours because drivers demonstrated:

a. willingness to refuel anywhere along their way or not far out of their way, and
b. reluctance to refuel close to home when it's in the wrong direction from home, if there are more convenient options available
c. rarity of refueling on single-purpose round trips from home as they frequently do for shopping, school, or social trips.

The main message is that drivers minimize travel time, both in their route choices and their refueling station choices, and location models should be consistent with this behavior. Among the models based on arcs, paths, and tours, the choice of model is less a matter of behavioral realism and more a function of data availability, model complexity, and the degree to which they can track this time-minimizing behavior accurately.[3]

In a modeling study comparing point-based and flow-based models, Upchurch and Kuby (2010) pointed out secondary advantages of locating stations using path-based models. Path-based models tend to place stations at high-flow locations while also making sure that different high-flow locations are capturing different sets of flows and/or providing a needed second or third fill on longer trips. One secondary advantage of such models is that they do better at achieving proximity to residential zones than the point-based *p*-median model does at intercepting origin-destination trips. Secondly, maximizing passing flow volumes will put stations where they are much more likely to remain optimal as more stations are added to the network. In contrast, locating stations to minimize travel distances from residential areas can lead to highly suboptimal station distributions as more stations are added.[4]

Finally, many reports about planning starter networks for hydrogen fueling and EV charging have emphasized the need for connecting stations that make longer trips possible (California Air Resources Board, 2016). By locating stations at high-flow intersections, but also spreading these sites over a wider megapolitan region, non-overlapping sets of shorter trips as well as longer trips requiring multiple fueling stops can be conveniently refueled in a time-minimizing manner.

6. Conclusions

The urgency of the climate-change challenge calls for immediate action to reduce GHGs from the cars on which 86% of Americans—and rapidly increasing numbers of people in the developing world—rely (Sperling and Gordon, 2010). To this end, this paper exhaustively reviewed the admittedly limited literature on revealed preference studies of where AFV drivers choose to refuel or fast-charge their vehicles when faced with a very sparse refueling network. Refueling preferences of AFV drivers have been revealed through surveys about current behavior, intercept surveys, and GPS and card-swipe data. These few existing studies suggest that AFV early adopters care more about location than price and adapt by refueling more frequently at higher tank or battery levels, more habitually at the same stations, more on work-anchored trips, more mid-trip, less frequently near home than on their way, and deviating farther off their fastest routes, compared with drivers of gasoline and diesel vehicles.

The revealed preference literature on station choice suggests some preliminary strategic implications for rolling out a start-up refueling station network. The revealed willingness of drivers to refuel farther from home, in the middle of their trips, and near freeway interchanges makes it possible to locate stations in areas through which major highways carry hundreds of thousands of drivers daily. While neighborhood refueling may represent the ideal option for consumers, such a strategy can only help a limited population in the early stages of infrastructure development when only a handful of stations are built. Neighborhood refueling, however, can be an excellent strategy if stations are located close to freeways where they can serve large traffic volumes traveling in multiple directions, including long-distance trips, while simultaneously serving traffic funneling into and out of targeted neighborhoods.

These revealed preference studies point out the pitfalls of generalizing from typical gasoline refueling behavior to alt-fueling behavior. Early adopters must adapt to the sparse availability of stations, which forces them to change their behavior. Likewise, it is risky to rely on stated-preference surveys about AFV adoption because usually only one station availability criteria is included in the survey, and respondents may answer based on their gasoline driving experience. Gasoline drivers can usually find one or more station on their way *and* close to their home no matter which way they are going—which is decidedly not the case for early AFV adopters.

Much additional research needs to be done to test these preliminary findings in other settings, with different densities of stations and with drivers at different stages of the adoption curve. Similar revealed-preference studies need to be repeated in more consumer-oriented areas, in less freeway-centric cities, in smaller cities and towns, on long-distance trips, and in other countries. More studies are needed of other types of AFVs. EV battery capacity and charging speed are increasing rapidly. Home charging may or may not obviate need for a charging station near home. More work is needed on refueling station choice by ethanol (E85) and biodiesel, and plug-in hybrid electric vehicle drivers, but given that these bi-fuel cars can also be filled with regular gasoline or diesel or be plugged in at home, their drivers might have less tolerance for inconvenience.

Finally, revealed preference for refueling locations necessarily focuses on drivers who already own or lease an AFV. An important unknown is whether time-minimizing, on the way, mid-trip, short-deviation refueling behavior is *learned* after purchasing an AFV, or do the buyers realize beforehand that this is how they are going to refuel? This is a critical question because the initial roll-out of stations must be sufficient to convince adopters to purchase an AFV in the first place. The revealed preference studies reviewed here do not reveal how the drivers evaluated the refueling network at the time they were considering their purchase.

[3] Arc-based models represent drivers refueling *en route*, but cannot track how many vehicles on one arc continue onto the adjacent arcs, which could lead to double-counting of flows and artificial criteria to keep stations from being placed on adjacent arcs. Path-based models track multi-arc routes, and models based on the flow-refueling location model (FRLM) have the added advantage of making sure that the entire round trip is feasible without running out of fuel given the driving range of vehicles and multiple stops along the way. Yet the path-based (flow-based, trip-based) models similarly fail to recognize that trips may be strung together into chains or tours, and drivers do not need to refuel somewhere on each trip in the chain. Models using tours, trip chains, and trip bundles are thus more behaviorally realistic than those using single O-D pairs, but the data availability and modeling complexity are increasingly challenging. For EVs, the gold standard of behavioral realism are the time-space activity-based models that factor in the charging time, drivers' time constraints, and even destination choice, but the data and modeling challenges escalate even further.

[4] This instability can be visualized by thinking of locating one station in the center of an area to minimize travel distances. When locating two stations, however, each one should be centrally located within the half of the region to which they are closest. The single station in the center of the region most likely would not be even close to the optimal position of either station in the 2-station optimum solution. In contrast, the highest flow 1-optimum remains optimal in the solutions for 2, 3, … *p* stations, as do most of the high-flow locations chosen (Upchurch and Kuby, 2010).

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